Progress in 1991-1992

ACTIVE CONTROL OF COMPRESSOR SURGE AND STALL

by
C. Boussios, A.H. Epstein, E.M. Greitzer, G. Hendricks, J. Paduano, L. Valavani
Gas Turbine Laboratory
Massachusetts Institute of Technology
Cambridge, MA 02139

Having demonstrated in previous years the ability to model, identify, and control rotating stall, our research has concentrated in the past year on refinements and extensions to the compressor modeling developed for active control research. The areas in which progress has been made are: 1) refinement of the basic fluid mechanics based on identification results, 2) understanding the effects of distortion on wave detection, and 3) using the nonlinear form of the rotating stall model to simulate short-circumferential-extent waves. Three-stage actively stabilized compressor experiments supported this work, and further verified that rotating stall stabilization is a viable concept.

Background Refinement of Moore-Greitzer Model of Rotating Stall

By systematically exciting separate eigenmodes of the 3-stage compressor wave dynamics, we were able to extract a thorough, accurate set of parameters characterizing the dynamics of the system. These parameters represent first-of-their-kind measurements of the fundamental fluid mechanical behavior, obtained at the global response level (i.e. input-output transfer characteristics). Prediction of these parameters can also be conducted using the Moore-Greitzer rotating stall model. This model is based only upon the compressor's geometry and steady-state performance maps (including steady-state IGV deflection effects). Other, unsteady effects have long been suspected to exist, but their importance to the accuracy of the model were unknown.

The experimental identification results indicate that the effects of unsteadiness are indeed quite important to model. Therefore, an unsteady term has been added to the compressor total-to-static pressure rise performance characterization. A rough description of the effect of the unsteady term is as follows:

$$\psi(\theta,t) \sim \psi_{ss}(\phi(\theta,t)) - \tau_{us}\frac{\partial\psi}{\partial t}$$

where τ_{us} is a parameter which characterizes the time lag for the compressor to respond to changes in axial velocity coefficient. By proper choice of the compressor lag parameter, good correspondence between measured and theoretically computed homogeneous characteristics (eigenmodes) of the compressor response is possible (see Figure 1). Thus, for the first time, compressor wave dynamics have been verified to conform to a refined version of the Moore-Greitzer model, for a wide range of operating conditions, and for the first three modes of oscillation of the axial velocity waves.

This result, that compressor behavior is predictable based on the Moore-Greitzer model, gives us confidence to continue research with this model as a baseline tool. Extensions to past work on rotating stall detection and stabilization can be studied by imposing different operating conditions or boundary conditions on the model, and seeing the effect on the sensing and control problems. In the case of distortion, for instance, the upstream total pressure boundary condition can be changed to reflect the incoming distorted flow. The Moore-Greitzer model is otherwise unchanged. To study nonlinear wave dynamics, one need only retain the nonlinearity of $\psi(\phi)$ in the model. The influence of distortion and nonlinearity have been the focus of this past year's research and is discussed in the following sections.

Effects of Distortion on Wave Sensing and Control

Understanding and minimizing the adverse effects of inlet distortion may be the single most important contribution this work can offer. Because a significant portion of the stall margin requirement of modern high-performance engines is due to inlet distortion, improvements in this arena could impact installed engine performance and operating range significantly. Although this work is just beginning, we hope to soon have the capability to design controllers which are 'robust to distortion' - we will presently describe this goal. First, however, we will briefly review our current understanding of the effects of distortion on wave evolution and the related wave sensing problem.

Although the only change to the Moore-Greitzer model for rotating stall and surge is a change in boundary conditions, the effect on the behavior of axial velocity perturbations is quite complex. The simplest way to characterize the compressor response is using linearized waves superimposed on a nonlinear, circumferentially nonuniform background flow. Figure 2 shows a schematic comparison of perturbation wave behavior for undistorted and distorted flow. In the undistorted case, sinusoidal waves remain sinusoidal - thus Fourier coefficients evolve independently. This provides a natural way to decouple the eigenmodes of the system, for identification, estimation (wave tracking) and control purposes. In the distorted case, on the other hand, sinusoidal waves do not remain sinusoidal - the eigenmodes cannot be decoupled using Fourier decomposition.

We have the capability to compute the eigenmodes of an axial compressor with any given inlet distortion, and to subsequently simulate the response of the compressor to flow perturbations. We have used this simulation to test wave tracking schemes. Wave tracking schemes used in the clean-inlet case rely on Fourier decomposition of hot wire data and subsequent plotting of the phase and magnitude of the sinusoids (first, second and third spatial coefficient). Figure 3 shows the results of this approach when applied to simulations of distorted-flow compressor response. The phase of the first Fourier coefficient does not travel in a straight line - that is, the first sine wave does not travel at a constant speed around the annulus - because it *participates in several eigenmodes of the compressor response*. Thus distortion must be taken into account to allow wave tracking to be successful.

One way to improve wave tracking is to apply a band-pass filter at the frequency of the eigenmode of interest. The resulting signal participates only in the corresponding eigenmode, and wave tracking can proceed as before. Figure 4 shows the results of this approach, using the same simulation data as in Figure 3. The estimated wave phase and the actual phase of the most unstable system eigenmode are shown to track each other modulo 2π - the band-pass filter successfully isolates the eigenmode of interest. Other schemes, such as using Kalman filtering to account for variations in signal-to-noise ratio in distorted flow, are possible. All such schemes rely on an understanding of the modeled effects of distortion on the complex wave dynamics.

For active control, one would like to develop a scheme which does not rely on the stationarity of the inlet distortion. One would also prefer schemes which do not rely on a priori knowledge about the distortion, or identification of the distortion shape. In other words, we would like to develop control laws which automatically adjust to changes in the inlet distortion pattern - i.e. they are 'robust' to inlet distortion. Thus current work is focused on modeling distortion as an external forcing function on the compressor dynamics. Such modeling introduces nonlinearities into the equations, which must be accounted for. It also requires careful modeling of the boundary conditions which one can realistically impose on the compression system - for instance, the potential modes of the upstream flow field depend not only on the ingested flow field, but also on the ccmpressor dynamic response to that flow field. Thus creating a meaningful input-output representation of time-varying distortions is a complex task. Initial work has begun in this area, and should pose challenging and relevant questions in the field of active control.

Simulating Nonlinear Stall Behavior

Progress has also been made with the realization, through theory and simulation, that a wide variety of stall inception behaviors exist *within the context* of the Moore-Greitzer model. The fundamental factor which effects the way that stall inception proceeds is the *shape of the nonlinear compressor characteristic*, $\psi(\phi)$. The differences which can occur when this shape is changed are dramatic - and they may explain why some compressors exhibit pre-stall waves which are more pronounced than those in other compressors. The implications for rotating stall control are equally dramatic, and have pointed to some new, important research directions and goals. We will detail a few of these here.

Up until recently, linearization of the Moore-Greitzer equations has been used to explain the evolution of small amplitude waves in axial compressors. This linearization is justified, and yields consistent results, for a large class of compressors. Some compressors, however, exhibit stall inception characteristics which differ (to varying extents) from those predicted by the linearized model. In an effort to explain this discrepancy we have turned to nonlinear simulation of stall inception, with the following result: compressors *can* be grouped into classes, depending on the shape of their compressor characteristics, and the stall inception behavior predicted by the *nonlinear* Moore-Greitzer model will be substantially different for each of these classes. Correlation of these results with experimental data has yet to be accomplished, but qualitative comparison of behavior is promising.

Some interesting 'classes' of compressor characteristics that have been simulated to date are: 1) flat-peaked, 2) stable-side steep, and 3) unstable-side steep. These types are shown in Figure 5. The stall inception behavior for flat-peaked characteristics is, as one would expect, well predicted by the linearized model - long periods of pre-stall wave activity precede growth into rotating stall. Stable-side steep characteristics exhibit small-amplitude limit cycles prior to stall, because large amplitude waves experience a stabilizing influence which is greater that the destabilizing influence of the unstable part of the characteristic. Thus, in this case as well, the compressor should exhibit long periods of small-amplitude wave oscillation prior to stall. Thus the nonlinear modeling confirms that in many cases, waves should precede and grow into rotating stall.

The final class of compressors is the unstable-side steep characteristics, for which the nonlinear effects are strongly unstable. Such compressors will tend to exhibit nonlinear transients into rotating stall, even when initial perturbations are quite small. Thus we expect that for these compressors, pre-stall waves will be difficult to detect.

The important point here is that *such compressors may still obey the dynamic model we have proposed.* Thus a rational approach to control law design for these compressors may still be possible.

Transients into rotating stall for a characteristic of type (1) and a characteristic of type (3) are shown in Figure 6. The following observations are important to note: The type (1) response is very much like that exhibited by the compressors at the Gas Turbine Laboratory - long precursors growing smoothly into stall. Linearized dynamics sufficiently characterize these compressors, making stabilization possible. The type (2) compressor exhibits no precursor (the initial wave magnitude is big enough to elicit nonlinear effects). Most important to note is that the nonlinear stall cell has *short circumferential extent* - that is, it looks like a spike traveling around the annulus, and contains higher harmonics. This behavior has been seen in some compressors, and this is the first time a theoretical prediction has shown similar behavior.

A control-theoretic version of the nonlinear Moore-Greitzer model has been developed. This model can be used to study control schemes which will stabilize disturbances *when nonlinearities are important.* Thus, for instance, if a highly localized disturbance (possibly driven by three-dimensional or tip-clearance effects) begins to grow and rotate around the annulus, eventually the global flow will be perturbed by the disturbance. If the disturbance is very sharp (short circumferential extent), nonlinear effects will be important. However, if the global nonlinear dynamics can be actively stabilized, such a disturbance will never grow into rotating stall. Thus the nonlinear dynamic model of rotating stall is a first step toward a more robust and universally applicable theory of compressor stall stabilization.

Planned Research

The research described above is very much work in progress. We are in the process of extending these modelling concepts to include characterization of the system forcing functions (distortion and engine environment perturbations). Experiments are planned on a 3-stage, low speed, axial compressor and on a small (650 hp) centrifugal compressor-equipped gas turbine engine.

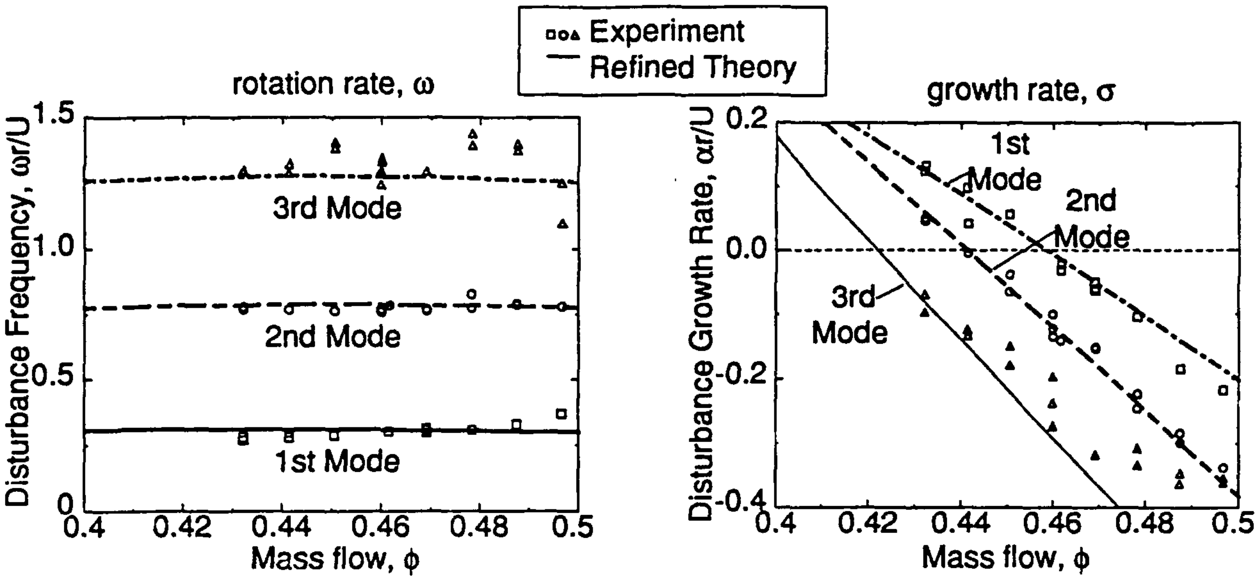

Figure 1: Comparison of refined theoretical and identification results, for the eigenvalues of the first three Fourier coefficients, (three-stage compressor data)

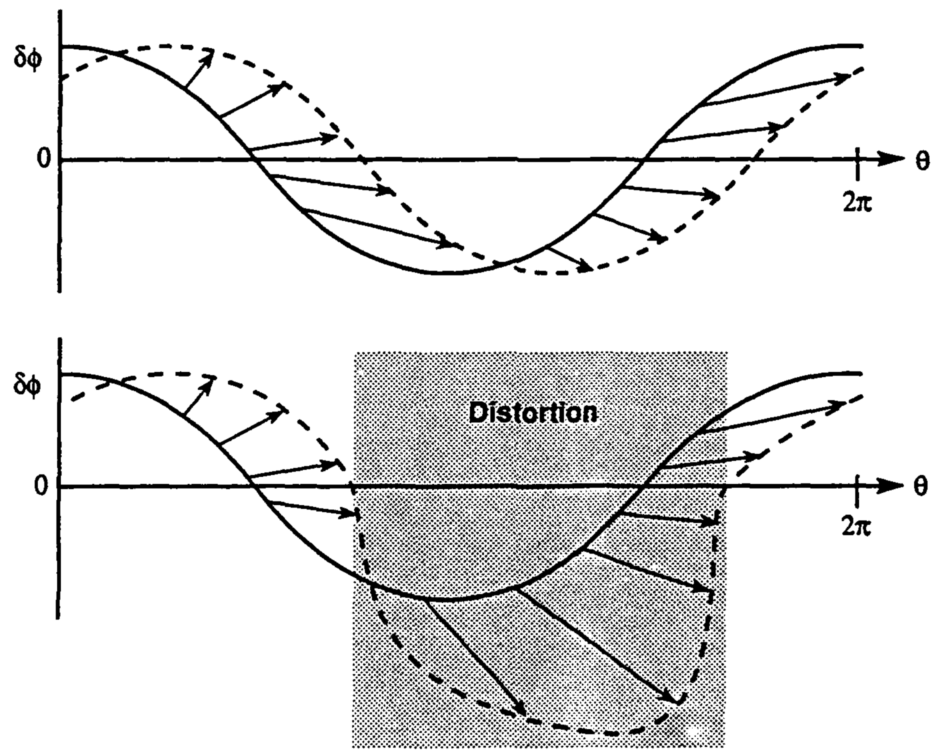

Figure 2: Wave evolution with and without distortion

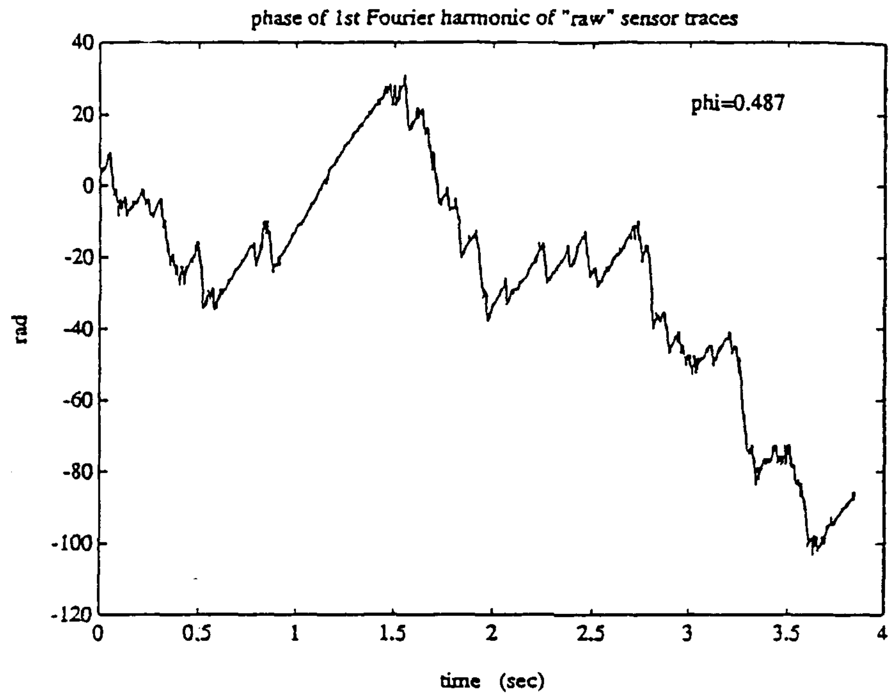

Figure 3: Estimated wave position using the phase of the first Fourier coefficient; distorted flow simulation.

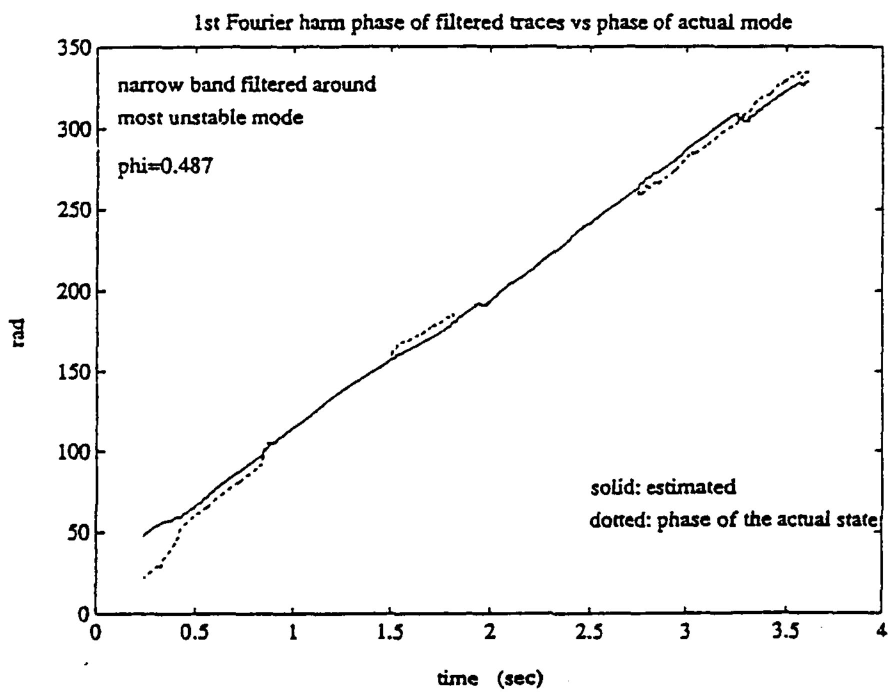

Figure 4: Estimated and actual wave position using filtered first Fourier coefficient; same simulation as in Figure 3.

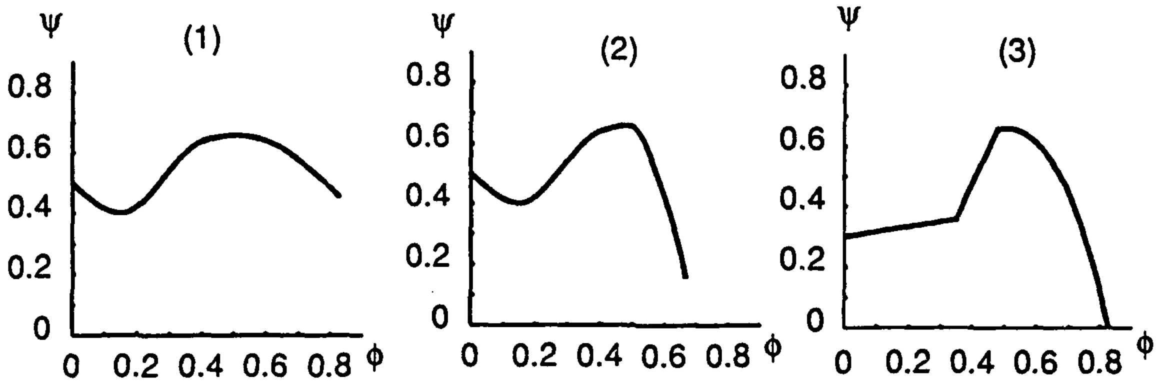

Figure 5: Examples of compressor pressure rise characteristics of different types: (1) flat-peaked, (2) stable-side steep, (3) unstable-side steep.

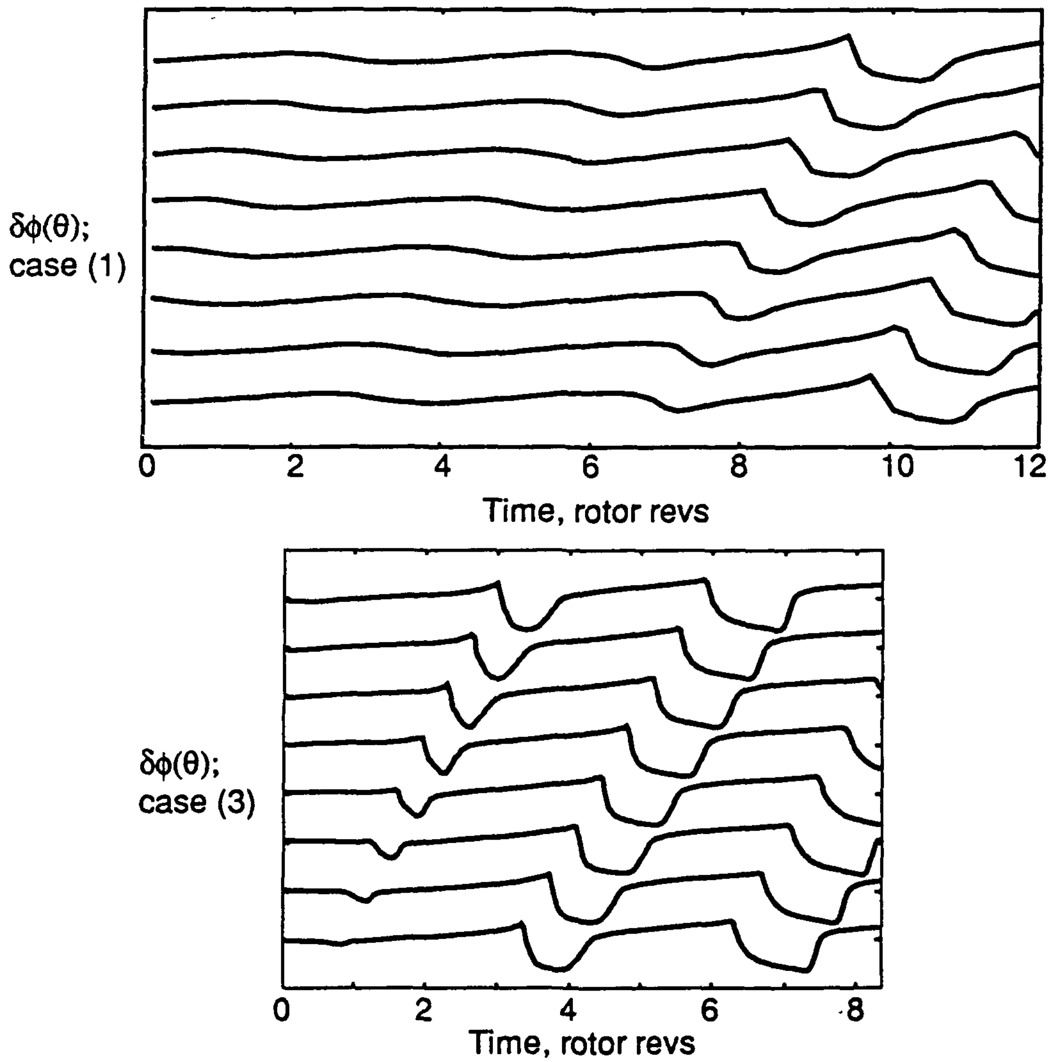

Figure 6: Time histories of rotating stall inception for the characteristics in Figure 5: (1) flat-peaked characteristic (3) the unstable-side steep characteristic.

GAS TURBINE LABORATORY
DEPARTMENT OF
AERONAUTICS AND ASTRONAUTICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

ROOM
TELEX 92-1473
FAX (617) 258-6093

(617) 253-
CABLE MIT CAM

12 May 1992

Mr. Eric Hendricks
Code 574B
Naval Command, Control & Ocean Surveillance Center
RDT&E Division
San Diego, CA 92152-5000

Dear Eric:

Enclosed please find the summary technical report on our past year's research under the ONR Accelerated Research Initiative on Active Control. Also included is a short summary of the significance of the MIT work.

I look forward to seeing you at NAPC on July 2. Please call if you have any questions.

Sincerely,

Alan

Alan H. Epstein
Professor and Associate Director,
Gas Turbine Laboratory

Encl.

cc: H. Rathbun
C. Morse, OSP 75384

AHE/dp

Check dist. list — cy should probably go to ONR Res Rep. too

SIGNIFICANCE OF MIT WORK TO THE DISCIPLINE OF ACTIVE CONTROL

MIT has invented the field of active stabilization of jet engine compressors, including originating the concept, establishing the underlying theory, and conducting the first experimental verification. We might consider the significance of this work in two senses: to airbreathing propulsion and to the more general field of active control.

Active compressor stabilization holds the promise of significantly improving many aspects of military and civil aircraft performance. By relaxing one of the fundamental constraints of jet engine design (surge and stall), it enables new engineering solutions, thereby improving maneuverability, fuel consumption, weight, and perhaps noise. For example, quantitative systems study has shown that active control can yield 10% reductions in aircraft gross takeoff weight for advanced fighter aircraft. The technology at MIT has progressed under this program from the initial concept to 6.2 studies on helicopter engines and at Air Force Test Facilities (although much basic research remains to be done).

In the area of basic research, the active compressor stabilization research has shown how a theoretical advance (the Moore-Greitzer hydrodynamic stability model), a conceptual innovation (active control of high energy fluid systems), and the microelectronic revolution can combine to dramatically change the direction of an established technology (compressor aerodynamics). Aside from the scientific contributions, the work can be viewed as a canonical example of active control of fluid systems, the only one of which we are aware in which a complicated internal flowfield of engineering interest has been controlled and in which elements are transitioning to 6.2.